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The extent of continental material in oceans: C-Blocks and the Laxmi Basin example

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SUMMARY

We propose a tectonic interpretation for the outer-SDRs (SDRs: Seaward-Dipping Reflectors) and Pannikar central ridge in the aborted Laxmi Basin west of India from wide-angle seismic reflection data. The outer-SDRs comprise syn-tectonic extrusives (lavas and/or volcanoclastics) emplaced above passively exhumed mid-to-lower mafic crust of continental origin. They erupted following sudden lithosphere weakening associated with isolation of a continental block (a 'C-Block'). Continuous magmatic addition during crustal extension allowed stretching of the lower crust whilst maintaining constant or even increasing thickness. A similar process occurred at both conjugate margins allowing bulk, pure-shear plate separation and formation of linear magnetic anomalies. The Laxmi example can explain enigmatic features observed in mature oceans such as presence of distal buoyant plateaus of thick continental crust away from the margins.

Key words: Indian Ocean; Crustal imaging; Continental margins: divergent; Continental tectonics: extensional; Crustal structure.

1 INTRODUCTION

Volcanic passive margins (VPMs) form when continental extension is coeval with extensive mantle melting (e.g. Skogseid 2001). On-shore surveys, coring and offshore deep-penetration seismic reflection profiles show that upper-crustal extension at VPMs is accommodated by both dyking (e.g. Klausen & Larsen 2002; Kendall *et al.* 2005) and major continentward-dipping detachment faults (e.g. Larsen & Jakobsdóttir 1988; Geoffroy *et al.* 2001, 2015; Stica *et al.* 2014). These faults bound thick wedges of syn-tectonic seaward-dipping volcanics that constitute the inner seaward-dipping reflectors (SDRs; Fig. 1).

At VPMs, successive SDR wedges grow from continent to ocean (Fig. 1a). We distinguish inner- and outer-SDRs (Planke *et al.* 2000). Inner-SDRs develop during extensional necking of the continental crust (Geoffroy 2005; Geoffroy *et al.* 2015, Fig. 1a). When observed, their bounding faults die out along the top of a thick lower crust characterized by high seismic velocities (HVLC, e.g. Schnabel *et al.* 2008; Funck *et al.* 2017) and strong reflections (e.g. White *et al.* 2008; Geoffroy *et al.* 2015). This lower crust is best interpreted as heavily sill-injected continental crust (e.g. White *et al.* 2008; Geoffroy *et al.* 2015). Its upper part (LC1 in Fig. 1a)

contains large-scale solid-state-flow structures associated with continental extension and continentward shear such as kilometric-scale S-C structures (Clerc *et al.* 2015; Geoffroy *et al.* 2015, Fig. 2a).

Ongoing excessive 'seaward' (or, rather, outward) magmatism and extension builds geometrically distinct distal outer-SDRs (Figs 1a and b, Planke *et al.* 2000; Franke *et al.* 2010; Quirk *et al.* 2014; McDermott *et al.* 2018). These are more arcuate than inner-SDRs (Fig. 1b) and associated with a high-velocity magmatic crust, which is thicker than averaged oceanic-crust (>7 km, Fig. 1a). This crust shows a low- to subhorizontally dipping Moho, in strong contrast to the necked, inner-SDR domain (Fig. 1). As observed in the S and NE Atlantic oceans (Franke *et al.* 2010; Quirk *et al.* 2014; McDermott *et al.* 2018), outer-SDRs are bent over a flat-lying horizon which divides the crust into two parts (Fig. 1b). In the S Atlantic, the crust beneath the outer-SDRs has a similar velocity structure to continental ductile middle crust LC1 observed beneath the necked part of VPMs (Geoffroy *et al.* 2015). This is also seen in the NE Atlantic when both reflection and refraction data are available (White *et al.* 2008; Funck *et al.* 2017). A third type of crust may exist at the extremity of VPMs. It is characterized by flat-lying igneous flows in the upper section and has been interpreted as non-oceanic crust

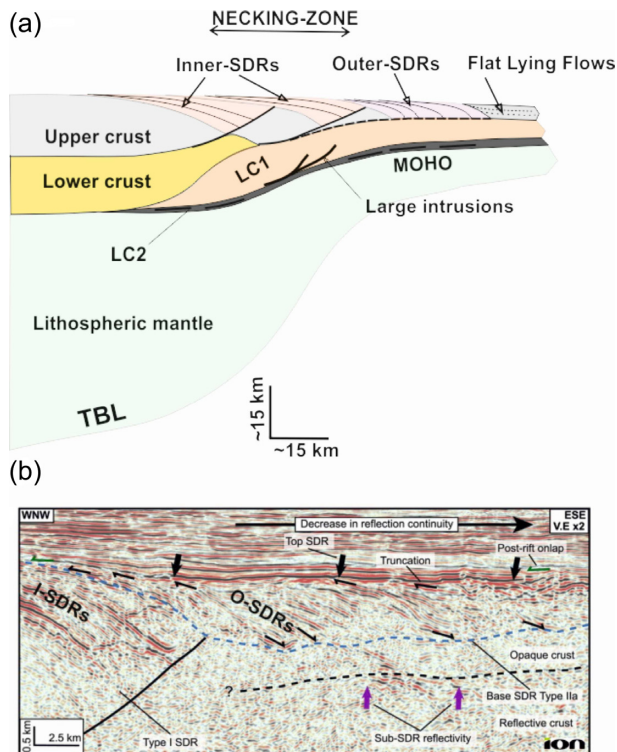


Figure 1. (a) Sketch of a volcanic passive margin with crustal types. LC1 and LC2: high-velocity continental lower-crust (see Geoffroy *et al.* 2015). TBL: lithosphere thermal boundary layer. (b) Transitional region between the inner-SDRs (here labelled by the authors Type I-SDRs) and outer-SDRs (here labelled by the authors Type II-SDRs) offshore Uruguay (from McDermott *et al.* 2018). See also Pindell *et al.* (2014). Note the flat-lying base of the outer-SDRs.

(Franke *et al.* 2010; Soto *et al.* 2011; Geoffroy *et al.* 2020). We refer to this type of crust herein as FLF-crust (Fig. 1a).

Our understanding of the SDRs, and especially outer-SDRs, is currently incomplete (Fig. 2). Outer-SDRs are generally considered to be associated with enigmatic oceanic-crust accretion (e.g. Franke *et al.* 2010; Paton *et al.* 2017) as inner-SDRs were earlier thought to be (e.g. Mutter *et al.* 1982). The gravity-driven flexure model for paired SDR wedges (either inner- or outer-, e.g. Buck 2017) involves the feeding of SDR lavas by an axial, lithospheric-scale, feeder dyke with magma injected from bottom to top. Following each magma injection and dyke cooling event, the localized increase in weight of the lithospheric column results in downward flexure of the newly erupted surface lavas. As described hereafter, this model does not match common observations at exposed inner-VPMs and in many seismic reflection studies. Not only are major normal listric faults with throws of over 2 km observed bounding the fan-shaped lava wedges, but angular unconformities due to secondary synthetic faults are common in SDR piles (e.g. Geoffroy *et al.* 2001; Pindell *et al.* 2014; McDermott *et al.* 2018; Chauvet *et al.* 2019). Inner-SDRs thus appear to develop in a similar way to hanging-wall basins on roll-over anticlines associated with listric detachment-type faults dipping continentward. In addition, many dykes crosscut inner-SDRs during their development at any location, most of them feeding the upper lavas at considerable distances from the edges of SDR wedges and related major faults (Klausen & Larsen 2002; Lenoir *et al.* 2003; Abdelmalak *et al.* 2015). This indicates that the magma is not all injected from a stable, permanent axial zone, a fundamental starting point in the model of Buck (2017) for a single

SDR wedge. Dykes beneath SDRs or cross-cutting them during their development are usually thin—less than 6 m on average in East Greenland (Klausen & Larsen 2002) and less than 4.5 m in Iceland (Gudmundsson 1983). Considering dykes to be mode-I cracks in an elastic medium, they are of moderate vertical extent and probably restricted to the upper crust (e.g. Gudmundsson 1983). Mafic dykes in active volcano-tectonic systems (e.g. Einarsson & Brandsdóttir 1980; Sigmundsson *et al.* 2014; Grandin *et al.* 2011) and in SDRs (e.g. Callot & Geoffroy 2004) propagate predominantly laterally away from the localized magma chambers that feed them. Those chambers and their distribution thus exert the primary control on magma feeding.

The mechanisms of formation of outer-SDRs (Fig. 1b) are not constrained by direct observation. Iceland could be the only place worldwide where SDRs of Neogene age do outcrop close to an acknowledged oceanic rift (e.g. Palmason 1981). Considering the distance from nearby inner-VPMs (E-Greenland and Faroe Islands) it is possible to assume that SDRs in Iceland are outer-type. The few detailed structural surveys from the eroded part of the island would show development similar to that associated with inner-SDRs, that is fault-controlled (Bourgeois *et al.* 2005). This was also the conclusion of Planke *et al.* (2000) from seismic reflection data collected at several VPMs worldwide. Admittedly, however, our knowledge on the origin of outer-SDRs as well as on the type of middle/lower crust (oceanic or continental) underlying them, remains incomplete. We tentatively address this topic below by considering the mode of continental breaking-up at VPMs

It is observed that syn-magmatic detachment faults bounding inner-SDRs dip continent-ward at conjugate VPMs (Fig. 2a). From the onset of continental extension such geometry at a developing pair of conjugate margins must partition between them a continental block (C-Block). The C-Block is the common footwall of the continentward-dipping detachment faults controlling the inner-SDRs development (Fig. 2a). Recent thermomechanical modeling supports this geometry and suggests that the existence and stability of such C-Blocks depend on the existence of an initial high-viscosity layer (LC2) in the lowermost, pre-extension, continental crust (Geoffroy *et al.* 2015). As the outer-SDRs develop, the C-Block is expected to evolve, forming a progressively more dissected and extended magma-intruded microcontinent (Fig. 2b).

To date, C-Blocks and the tectonic relationships between them and outer-SDRs have not been reported. In this paper we present the first case-history of a C-Block between aborted conjugate VPMs in the well-studied Laxmi basin, west of India. The relationships between this C-Block and nearby outer-SDRs bring into question the nature of outer-SDR lower crust and, by extension, the definition of the continent–ocean transition across VPMs. Finally, we propose a tectonic model for outer-SDRs in the light of our findings.

2 THE LAXMI RIFT SYSTEM

The Gop and Laxmi basins formed before the Arabian Sea and lie between it and the Indian craton (Fig. 3a, Minshull *et al.* 2008). In the Arabian Sea, syn-magmatic break-up occurred between the Seychelles and a basement high, the Laxmi Ridge (Misra *et al.* 2015). The earliest oceanic accretion in the Arabian Sea occurred at C28n (Paleocene, Collier *et al.* 2008, Fig. 3a) immediately after extrusion of the Deccan Traps at C29r (Courtillot & Renne 2003).

North of 18°N, the Gop basin trends approximately EW. It is bounded to the south by a *ca.* 17-km-thick ridge, the N-Laxmi Ridge, probably of continental affinity (Minshull *et al.* 2008, Fig. 3a). The

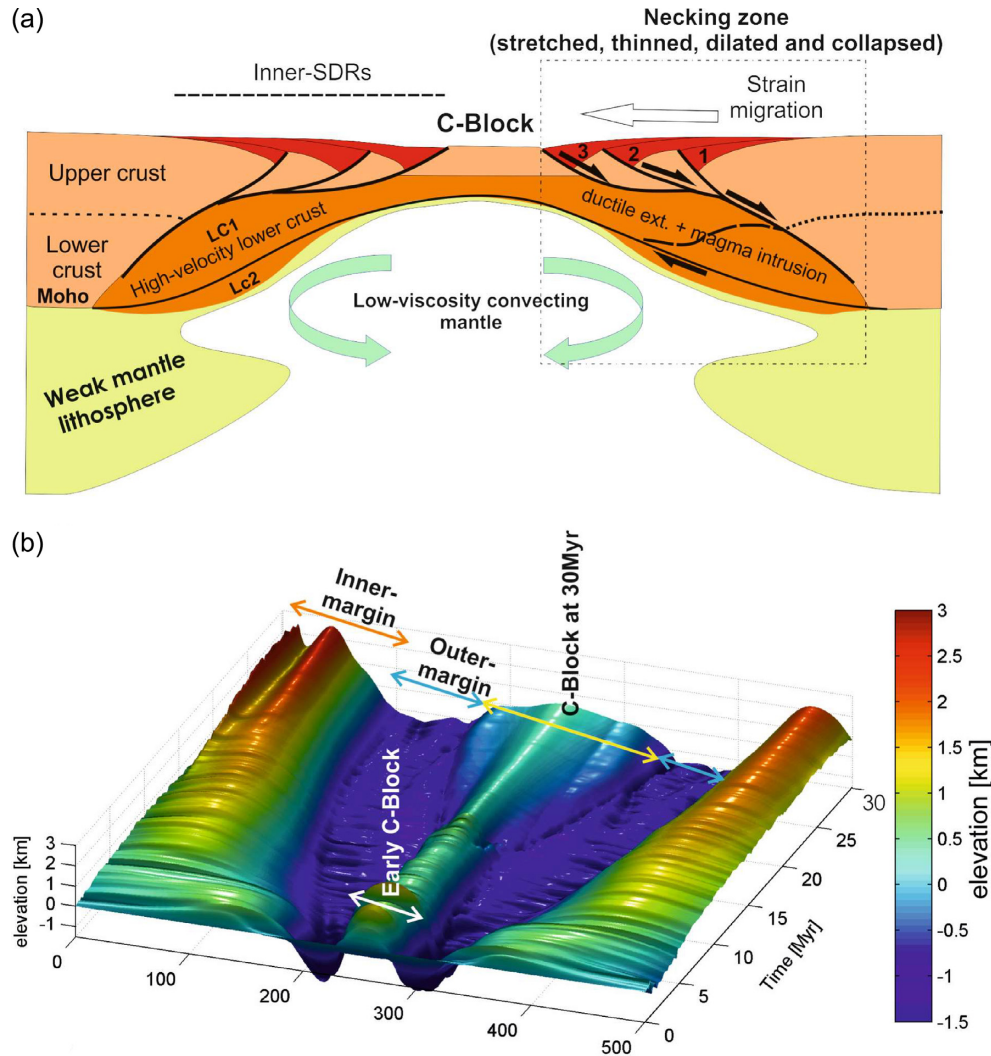


Figure 2. Top panel: conjugate VPMS at the initial necking stage, before the formation of outer-SDRs. There is no oceanic lithosphere at this stage. The inner-SDRs develop sequentially (1–3, right-hand side). LC1 is highly mobilized, magma-injected middle-lower continental crust and LC2 is supra-Moho mafic lower crust acting as a rigid lid over convecting mantle below. Bottom panel: basement depth evolution of paired conjugate VPMS with time over a 30 Myr period. This figure is the outcome of a thermomechanical modelling involving mantle melting (from Geoffroy *et al.* 2015). It notably illustrates (1) the C-block evolution with time, (2) its buoyancy and progressive dislocation and widening with time, (3) the shallow depth of the basement on both sides (outer-SDR basement domain) and (4) the increasing topography of the inner parts of the margins (inner-SDRs domain).

central part of the Gop basin, the so-called Gop Rift, may be oceanic although the crust is thicker and with lower seismic velocity than that beneath the nearby oceanic Arabian Sea (Minshall *et al.* 2008). Both the Gop Basin and the N-Laxmi Ridge lie parallel to the earliest Arabian Sea magnetic anomaly A28 (Fig. 3a). This led Collier *et al.* (2008) to propose a sequential magmatic break-up history from the Gop Basin in the north, to the Arabian Sea in the south.

Further south, the NNW-trending Laxmi Basin and S Laxmi Ridge are clearly oblique to Arabian Sea magnetic anomalies and transforms (Eagles & Hoang 2014, Fig. 3a). A transform-like fault system separates the S Laxmi Ridge from Arabian Sea oceanic crust (Figs 3b and c, Misra *et al.* 2015). The Pannikar Ridge lies in the middle of the Laxmi Basin and features a positive Free Air gravity anomaly in the north that reduces and becomes negative to the south (Fig. 3a). A positive linear magnetic anomaly is also discernable along the northern part of the Pannikar Ridge (Fig. 3a). Linear magnetic anomalies have been described in the Laxmi basin on both sides the Pannikar Ridge (Bhattacharya *et al.* 1994, Fig. 3a).

The nature of the crust of the Laxmi Ridge, Laxmi Basin and Pannikar Ridge (hereafter referred as ‘Laxmi system’) is controversial. Bhattacharya *et al.* (1994) propose the Laxmi basin (and Pannikar Ridge) to be oceanic crust based on the identification of irregular magnetic anomalies. Talwani & Reif (1998) argue that the Laxmi Ridge was probably continental based on kinematic reconstructions. This is also suggested by Corfield *et al.* (2010) from gravity inversion. Misra *et al.* (2015) propose the whole Laxmi system to be oceanic crust on the basis, mainly, of the IONTM wide-angle seismic reflection lines. They notably interpret localized reflections in the deep lower crust as SDRs down to the Moho. For those authors, this would favor oceanic-type crust. Yet, such an assertion is unusual in the field of crust with SDRs, regardless of what is considered oceanic (e.g. Palmason 1981) or continental (e.g. White *et al.* 2008; Clerc *et al.* 2015). In contrast, Krishna *et al.* (2006) favour, for the Laxmi system, the hypothesis of stretched continental crust injected and covered with mafic magma. They base their conclusions on low seismic velocities in the middle crust (Figs 3b and c), the gravity

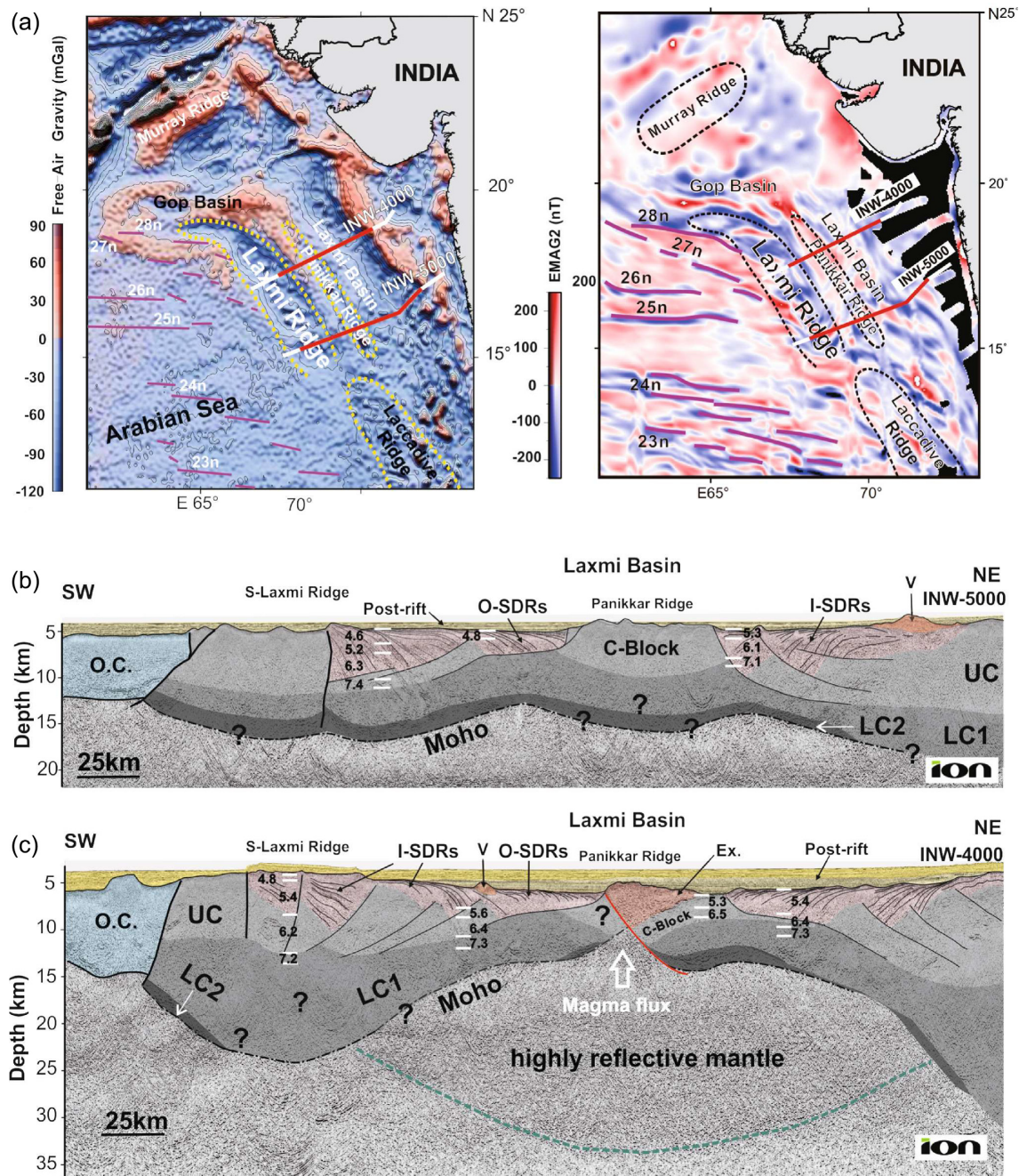


Figure 3. (a) Left-hand panel: WGM free air gravity of the Gop and Laxmi Basin (Bonvalot et al., 2012). Right-hand panel: magnetic anomalies from EMAG2 (v3, doi:10.7289/V5H70CVX). (b and c) INW-5000 and INW-4000 ION seismic lines. The buoyant Panikkar Ridge is interpreted as a C-Block cut from north (c) to south (b) by southeastward-propagating breakup. O.C.: oceanic crust. O-SDRs: Outer-SDRs, I-SDRs: Inner-SDRs, Ex.: extrusive/intrusive complex, V: volcano, UC: upper crust, LC1: lower crust type 1, LC2: lower crust type 2.

lows of the Laxmi and central Panikkar ridges (Fig. 3a) and the correlation of some of the observed magnetic anomalies (Fig. 3a) with mafic intrusive bodies mapped at the top of the basement. Guan et al. (2016) and Nemčok & Rybár (2016) recognized from the ION™ wide-angle seismic reflection data the typical pattern of conjugate VPMs and also interpret the Laxmi system as probably fully continental.

We reevaluated this crust using the ION Geophysical IndiaSPAN™ long-offset seismic reflection data (Figs 3 and 4). Our interpretation, described below, was constrained by the few

seismic refraction data that are available (Naini & Talwani 1982). In the upper-crust (extrusive sections) we distinguished seismic reflection facies and features using the classical volcano-stratigraphic seismic analysis of Planke et al. (2000), Rey et al. (2008) and Calvès e.gal. (2011). In the sub-SDR basement with high seismic velocities ($V_p > 7 \text{ km s}^{-1}$), we interpret, following several authors, seismic layering and/or high-amplitude oblique reflectors with positive polarities like single and/or group of subparallel mafic intrusions (or magma intruded along shear-zones, e.g. Planke et al. 2000; White et al. 2008; Clerc et al. 2015; Wrona et al. 2019).

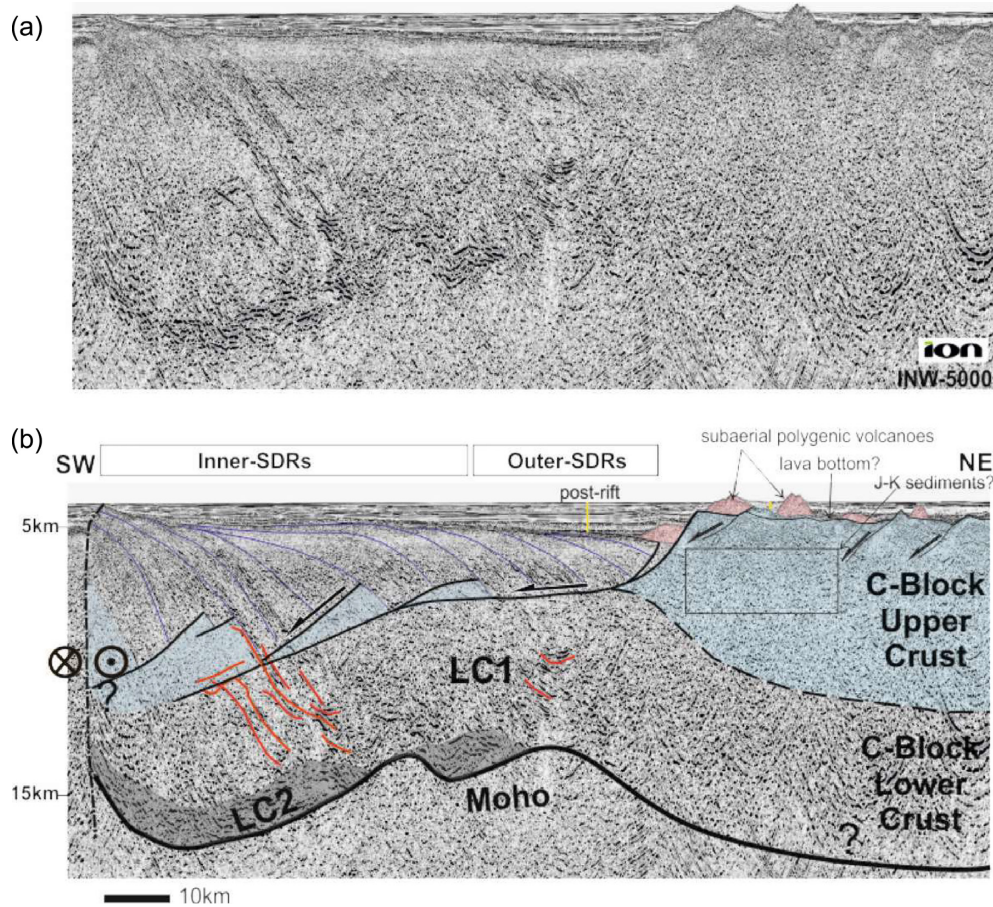


Figure 4. Detailed interpretation of the SW part of line INW-5000 (a: not interpreted, b: interpreted). Blue: probable upper crust. Red lines: mafic intrusions. Post-SDR sinistral strike-slip faulting is suggested to the left of the section along with post-SDR transtension during Arabian Sea breakup (see Fig. 3). Weak subhorizontal layering suggests post-rift sediments (see also Guan *et al.* 2019). In red: selection of high-amplitude positive reflectors interpreted as major sheet intrusions. Note that some of those intrusions appear to be late (postdating inner-SDRs).

In accordance with the interpretation of Nemčok & Rybár (2016) we find that the Laxmi Basin and bordering areas are an aborted continental extensional system with conjugate volcanic passive margins which probably developed from extended continental crust (Guan *et al.* 2019, Figs 3b and c).

The SDRs are well-developed across the INW-4000 and INW-5000 lines (Fig. 3). Both inner- and outer-SDRs are detected along the edges of the basin (Figs 3b and c). The SDRs face the central Pannikar Ridge (Fig. 3a) and present high-amplitude, linear magnetic anomalies (Krishna *et al.* 2006). We thus interpret the Pannikar Ridge in line INW-5000 as a C-Block. Its thickness is uncertain but is probably similar to Laxmi Ridge thickness visible in line INW-5000 (Fig. 3b). The C-Block (~40 km in length along INW-5000) was probably subaerial before thermal subsidence of the basin because large stratovolcanoes developed at its surface.

To the north (INW-4000; Fig. 3c), this C-Block is cut by a large fault, probably associated with southward propagation of an oceanic breakup axis (Guan *et al.* 2016; Nemčok & Rybár 2016). This fault may have functioned as a large-scale conduit that fed the 4-km-thick magma extrusion complex beneath which the basaltic upper crust flexed down (Fig. 3c). We interpret the reflective sub-Moho mantle beneath the break-up area as magma-impregnated mantle that fed the extrusive pile (Fig. 3c). Above the Moho, the lower crust is locally highly reflective with subparallel layers (LC2

in Geoffroy *et al.* 2015; see Fig. 1a). The overlying lower crust LC1 (see Fig. 1a) has seismic velocities of $7.2\text{--}7.4\text{ km.s}^{-1}$. These velocities are typical of the HLVC beneath VPMs (Bauer *et al.* 2000; Funck *et al.* 2017). LC1 exhibits disrupted high-amplitude seaward-dipping reflections, probably intrusions, a typical pattern of LC1 in the necked and sheared parts of VPMs (e.g. Clerc *et al.* 2015). Although they may locally parallel the upper-crust reflections (Misra *et al.* 2015), their higher amplitude clearly distinguishes them from the weaker reflective horizons in the upper-crustal SDRs (Fig. 4).

The outer-SDRs are especially well developed SW of the profiles (Figs 3b, c and 4). They have a regular accurate shape with a small radius of curvature. The extremity of the reflectors ends abruptly top of a crustal layer which is poorly reflective compared to the deeper crust and whose top is subhorizontal, similar to what is observed elsewhere beneath distal parts of the VPMs that have outer-SDRs (e.g. Franke *et al.* 2010; McDermott *et al.* 2018, Fig. 2). The $7 \pm 1\text{ km}$ thick lower crust beneath the outer-SDRs has seismic velocities of about 7.3 km.s^{-1} (Fig. 3c), typical of LC1 crust (Geoffroy *et al.* 2015). The Moho dips gently continent-ward. As observed elsewhere (see Introduction), outer-SDRs overlie at high angle a flat-lying subhorizontal horizon at the top of the reflective deeper crust. In both seismic profiles (Figs 3b, c and 4) a 'lateral' fault is visible W of the C-Block, apparently dying out along the flat-lying surface. In profile INW-5000, a symmetrical fault E of

the Pannikar Ridge is defined by data of somewhat lower quality (Nemčok & Rybár 2016).

3 A MODEL FOR OUTER SDRS AND C-BLOCKS

Laxmi Basin illustrates (1) the structure of conjugate VPMs with a central C-Block, (2) the relationship between SDRs and the C-Block and (3) the location of earliest break-up in this system. In the light of these findings, we propose a new tectonic model for outer-SDRs and C-Blocks as follows (Fig. 5).

The thin, sedimentary, post-rift sequence top of the C-Block suggests that it remained buoyant and subaerial or shallow long after the end of continental extension in the Laxmi Basin (Fig. 4). Carbonates are described top the volcanic basement highs in the area (Misra *et al.* 2017). The subhorizontal boundary marking the end of the seaward-dipping reflectors beneath the outer-SDRs is an important feature (Fig. 4). It is not a reflective horizon but a flat-lying discontinuity bounding two seismically distinct units—the outer-SDRs and the underlying crust (Fig. 1b; Franke *et al.* 2010). We interpret this horizon as a syn-magmatic detachment fault and the continentward-dipping, high-angle normal fault bounding the C-Block as the break-away fault (Figs 4b and A' in Fig. 5). This detachment appears to be located on top of crust characterized by seismic velocities typical of lower crust, which appears to be exhumed below syn-tectonic lavas to the SW of the C-Block (Fig. 4b). The outer-SDR lavas are rotated by both basal shear along the detachment fault and probably also by progressive loading by additional lavas (Palmason 1981).

In our model, the upper crust outboard of the C-Block solely comprises the outer-SDRs. Therefore, outer SDRs must form simultaneously to the exhumation of the continental middle-lower crust injected with syn-tectonic magma. In the active volcano-tectonic area new SDR-related lavas are fed by dykes and possibly also magma rising along the major fault zones (Quirk *et al.* 2014). Extension in the lower crust is facilitated by both ductile flow, possibly magma-assisted, and magmatic dilation through dyking. Coeval major sill emplacement maintains and even increases crustal thickness with time. Middle/lower crustal exhumation accompanies reduction in lithosphere strength when the C-Block becomes separated from the inner-VPM (Fig. 2). At this point continuity of rigid upper crust is lost and cannot be compensated by strength in the mantle lithosphere because of its high temperature (Kusznir & Park 1987; Geoffroy 2005; Gac & Geoffroy 2009; Burov 2011). This stage thus offers a definition for the mechanical breakup of the continental lithosphere that is not based on the onset of oceanic crustal formation. In other words, the *mechanical* breakup of the lithosphere may preserve the continuity of the compositional continental lithosphere. It defines breakup as a development phase related to plate-tectonic extensional forces reinforced by gravity-driven collapse (Pindell *et al.* 2014; Geoffroy *et al.* 2015, Fig. 2).

Our proposal is compatible with the depth-dependent deformation model of Huisman & Beaumont (2011). This predicts exhumation of the lower crust when early decoupling of the mantle lithosphere occurs in extending lithosphere in hot environments. In our model lower-crustal ductile stretching and continuous magmatic dilation brings about steady-state, pure-shear extension in the outer-part of VPMs. We call this steady-state process 'continental spreading' (Fig. 5). There is to date no seismic evidence for significant seaward, pressure-driven active channel flow of the lower crust during lithosphere break-up but we do not exclude it. In distal parts

of VPMs lower crustal exhumation could be a passive mechanism that follows detachment of the C-Block from the inner part of the margin (AA' in Fig. 5).

4 CONCLUDING REMARKS

The Laxmi Basin case example is important in that it illustrates the early stage of continental breakup in a magma-rich environment. Our seismic interpretation is supported by similar observations made elsewhere (e.g. Franke *et al.* 2010) and thermomechanical modelling of extension and breakup of warm continental lithosphere (Geoffroy *et al.* 2015). It includes important aspects of continental breakup relevant to passive margins elsewhere. We highlight the following main points.

1. The existence of a large buoyant C-Block as a consequence of conjugate VPM development agrees with theoretical models. In the Laxmi basin, breakup may occur in the middle of the C-Block (Fig. 3c). However, it could also occur adjacent to the C-Block which would then ultimately become part of the distal section of one of the VPMs. It is possible that C-Blocks are discrete features difficult to recognize in mature conjugate VPMs. This is especially true if frequent rift jumps occur during breakup.

2. The Laxmi basin example suggests that outer-SDRs may overlie highly intruded continental mid-to-lower crust with high seismic velocities. Seismic refraction studies show no significant lateral variation in velocities for the HVLC beneath inner- and outer-SDRs suggesting they may have a similar provenance.

3. At non-volcanic or magma-poor margins, extension of cold continental lithosphere is frequently associated with an early necking stage followed by later exhumation of serpentinized continental mantle (e.g. Boillot & Froitzheim 2001). Break-up of the crust predates that of the rigid mantle (Huisman & Beaumont 2011). At VPMs—hot mantle lithosphere has little or no strength (Callot *et al.* 2002; Gac & Geoffroy 2009). High thermal gradients result from small-scale convection, voluminous magma input and rapid extension (Lenoir *et al.* 2003; Gac & Geoffroy 2009). The time and space transition from inner- to outer-SDR formation is diagnostic of mechanical break-up of the whole continental lithosphere ('whole lithosphere failure'; Kusznir & Park 1987) as a consequence of the splitting of the C-Block from the inner-margin (Figs 2 and 5).

4. We distinguish two main areas at VPMs: the inner, continental, high-strength necking-zone with the inner-SDRs, and the mechanically weak spreading-zone with the outer-SDRs (or FLF), whose probable steady-state development is a combination of ductile extension and magma addition (Fig. 5). Contrary to former views (e.g. Paton *et al.* 2017), we see no objections to a continental origin of the crust underlying outer-SDRs even if this crust is highly magmatic. We do not claim that all outer-SDRs form in the same way or that other processes, which must be both geologically and mechanically realistic, may be encountered.

5. We infer from this study, onshore observations (e.g. Lenoir *et al.* 2003) and other seismic interpretations (e.g. Quirk *et al.* 2014) that tectonic extension operates simultaneously with mantle melting throughout the process of plate separation at VPMs. Dykes and sills continuously intrude the upper and lower crust, respectively. During the earliest stage of lithosphere thinning and mantle melting, horizontal and vertical magmatic dilation of the crust may be more important than stretching and thinning driven by far-field tectonic stresses (Klausen & Larsen 2002; Geoffroy 2005). No SDRs form at this stage. Volcanism solely builds subaerial plateaus of lava

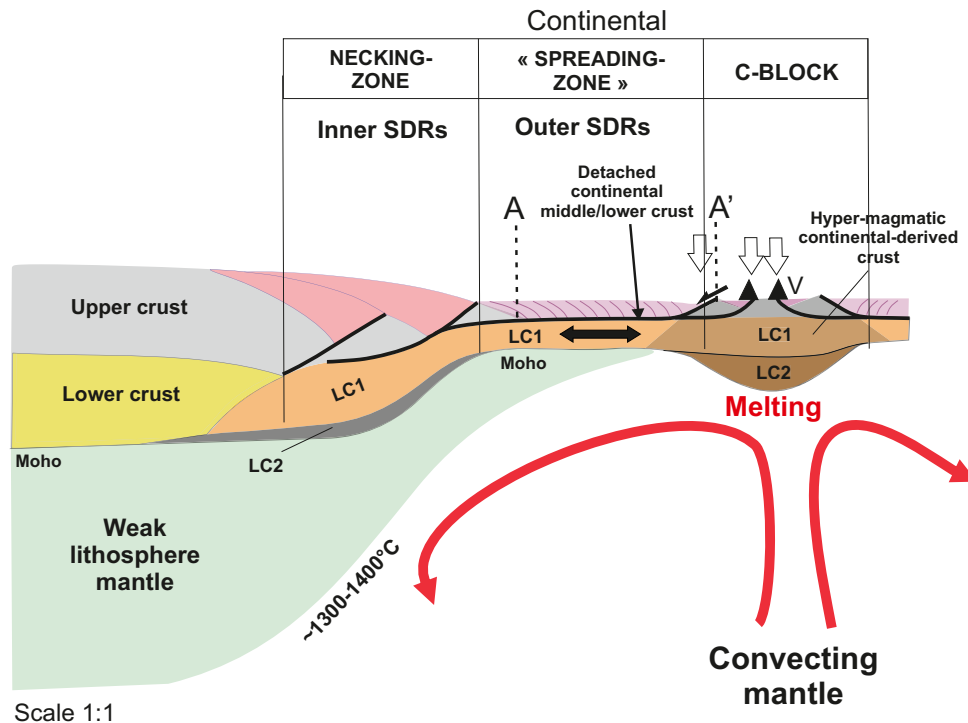


Figure 5. Tectonic model. Inner VPM upper-crust (left of A) is detached from the C-Block (A') along a subhorizontal plane. A' is the location of the breakaway fault. This is responsible for the passive exhumation of LC1 which is syn-tectonically covered by outer-SDRs over the active melting zone. Extension beneath the detachment surface is achieved via a combination of ductile crustal flow and magma dilatation. Divergence between the inner margin and the C-Block is driven by tectonic extension, gravity and magma dilation in the central active melting zone. C-Blocks may be very small, but they are suggested to be a geometric necessity to account for the geometry of inner-SDRs at conjugate VPMs. They may become indistinguishable with time due to their progressive digestion by on-going magmatism and bottom erosion due to mantle advection. V: volcanoes. Vertical white arrows indicate possible locations of final oceanic break-up (see also Fig. 3c).

flows and possibly hyaloclastites (Klausen & Larsen 2002; Geoffroy 2005; Planke *et al.* 2000). Strong, rapid lithosphere necking with SDR formation on the upper crust and lower crustal flow beneath, follows this initial, short-duration stage (e.g. Clerc *et al.* 2015; Geoffroy *et al.* 2015). Although huge amounts of magma continue to intrude the crust, high-rate tectonic thinning/stretching in the crust outstrips magma addition, thus enabling the crust to thin. Estimating lithosphere thinning and stretching (β factor) from the thickness of the crust only is thus not possible in magma-rich continent-ocean transition regions.

6. The Afar area is a magma-rich breakup region early in its development to which we can apply the model we describe above. A recent compilation of receiver function data (e.g. Hammond *et al.* 2011) suggests a crustal-thinning gradient similar to that observed at VPMs, with continentward-dipping faults accommodating extension (Stab *et al.* 2016). Inner-SDRs have been identified in the Ethiopian margin necking zone where crustal flexure is observed (Wolfenden *et al.* 2005). Away from this flexure zone, the Afar depression is underlain by crust 18–23 km thick with a gently dipping crust–mantle boundary (Stab *et al.* 2016).

By analogy with VPM sections, these observations could suggest that the active Afar depression is floored by outer-SDRs and/or FLF-crust (Fig. 1a). Although representing just one stage in a *ca.* 30 Myr tectonic period, this area illustrates that dyking from distinct upper-crustal magma chambers occurs during plate breakup (e.g. Wright *et al.* 2006). However, active and/or

very recent fault-accommodation of stretching and thinning also occurs in the area. This is observed both inside the central depression (Stab *et al.* 2016) and at the tip of both the southward-propagating Red Sea (the Danakil depression, Bastow & Keir 2011; Bastow *et al.* 2018) and the northward-propagating Gulf of Aden oceanic rifts (Djibouti, e.g. Manighetti *et al.* 2001; Geoffroy *et al.* 2014).

The relationship between the current extension and mantle melting processes is not fully understood. An important observation in the Afar depression is the apparent decrease in the effective elastic thickness (T_e) to values of <7 km west and south of the Danakil Block (Pérez-Gussinyé *et al.* 2009; Daniels *et al.* 2014). There, the crust is thick, however, with an apparent flat-lying or gently dipping Moho (e.g. Stab *et al.* 2016, and references therein). Taking into account the existence of early inner-SDRs bounding the depression (Wolfenden *et al.* 2005), or at least arrays of continentward-dipping faults (Stab *et al.* 2016), this T_e value would fit well a model of ongoing emplacement of outer-SDRs over a ductile crust similar to the Laxmi case. In such case, most of the plate effective elasticity would be located in the upper crust lava section. A key question would then be whether the Danakil area can be considered to be a C-Block. Another question is if an elongated volcanic system such as the Erta Ale (e.g. Pagli *et al.* 2012) can, or not, generate SDRs through isostatic response to the weight of lava accumulation (Bastow & Keir 2011) or axial dyke-swarm thickening with time. Also if such a spectacular feature is, or not, discernable in other, older volcano-tectonic divergent systems?

1. In oceans, it is difficult to distinguish ‘true’ oceanic crust from continent-derived mafic crust. Magma-rich continental breakup obscures the true extent of purely igneous oceanic lithosphere, not only beneath the margins but also further out in the ocean basins. Some continent-derived mafic crust may be thick (e.g. Rio Grande rise) and some thin (e.g. the Laxmi Basin) because of pre-magmatic extensional thinning and/or lower magma budget. Both crustal types (oceanic or VPMs) have high densities and similar seismic structure. Both also host linear magnetic anomalies, like this is observed in the Laxmi Basin above inner- and outer-SDRs (Fig. 3a; Bhat-tacharya *et al.* 1994). Because of their extrusive nature and seaward development with time (Geoffroy 2005, Fig. 2), SDRs are associated with linear but segmented magnetic anomalies (Larsen & Jakobsdóttir 1988; Behn & Lin 2000; Stica *et al.* 2014; Franke *et al.* 2019). Pairs of magnetic anomalies are also found in Afar where magmatic continental break-up is underway (Bridges *et al.* 2012). Therefore, linear magnetic anomalies are not unique to oceanic crust (Geoffroy *et al.* 2020);

2. Our model has implications for the structure of shallow oceanic plateaus some of which may be continental (Sager 2014; Foulger *et al.* 2020). Many such plateaus worldwide are near VPMs (König & Jokat 2010; Sager 2014; Stica *et al.* 2014). These plateaus may contain more continental material, including magma-injected continental lower crust and C-Blocks, than hitherto assumed. Targeted oceanic drilling programs and strategic dredging could test these ideas at specific locations.

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REFERENCES

- Abdelmalak, M.M. *et al.*, 2015. The ocean-continent transition in the mid-Norwegian margin: insight from seismic data and an onshore Caledonian field analogue, *Geology*, **43**, 1011–1014.
- Bastow, I. & Keir, D., 2011. The protracted development of the continent–ocean transition in Afar, *Nat. Geosci.*, **4**, 248–250.
- Bastow, I.A. *et al.*, 2018. The development of late-stage continental breakup: seismic reflection and borehole evidence from the Danakil Depression, Ethiopia, *Tectonics*, **37**, 2848–2862.
- Bhattacharya, G.C., Chaubey, A.K., Murty, G.P.S., Srinivas, K., Sarma, K.V.L.N.S., Subrahmanyam, V. & Krishna, K.S., 1994. Evidence for Seafloor Spreading in the Laxmi Basin, Northeastern Arabian Sea, *Earth planet. Sci. Lett.*, **125**, 211–220.
- Bauer, K. *et al.*, 2000. Deep structure of the Namibia continental margin as derived from integrated geophysical studies, *J. geophys. Res.*, **105**, 25 829–25 853.
- Behn, M.D. & Lin, J., 2000. Segmentation in gravity and magnetic anomalies along the U.S. East Coast passive margin: implications for incipient structure of the oceanic lithosphere, *J. geophys. Res.*, **105**, 25 769–25 790.
- Boillot, G. & Froitzheim, N., 2001. Non-volcanic rifted margin, continental break-up and the onset of seafloor spreading: some outstanding questions, in *Non-Volcanic Rifting of Continental Margins: A Comparison of Evidence from Land and Sea*, pp. 9–30, eds Wilson, R.C.L., Withmarch, R.B., Taylor, B. & Froitzheim, N., Geological Society, London, Special Publications.
- Bonvalot, S., *et al.*, 2012. World Gravity Map: Commission for the Geological Map of the World. BGI-CGMW-CNES-IRD Eds., Paris.
- Bourgeois, O., Dauteuil, O. & Hallot, E., 2005. Rifting above a mantle plume: structure and development of the Iceland Plateau, *Geodinamica Acta*, **18**, 59–80.
- Bridges, D.L., 2012. Magnetic stripes of a transitional continental rift in Afar, *Geology*, **40**, 203–206.
- Burov, E.B., 2011. Rheology and strength of the lithosphere, *Marine and Petroleum Geology*, **28**, 1402–1443.
- Buck, W.R., 2017. The role of magmatic loads and rift jumps in generating seaward dipping reflectors on volcanic rifted margins, *Earth planet. Sci. Lett.*, **466**, 62–69.
- Callot, J.-P., Geoffroy, L. & Brun, J.-P., 2002. 3D analogue modelling of volcanic passive margins, *Tectonics*, **21**, 1395–1408.
- Calvès, G., Schwab, A.M., Huuse, M., Clift, P.D., Gaina, C., Jolley, D., Tabrez, A.R. & Inam, A., 2011. Seismic volcanostratigraphy of the western Indian rifted margin: the pre-Deccan igneous province, *J. geophys. Res.*, **116**, B01101. doi:10.1029/2010JB008062.
- Chauvet, F. *et al.*, 2019. Eocene continental breakup in Baffin Bay, *Tectonophysics*, **757**, 170–186.
- Clerc, C., Jolivet, L. & Ringenbach, J.-C., 2015. Ductile extensional shear zones in the lower crust of a passive margin, *Earth planet. Sci. Lett.*, **431**, 1–7.
- Callot, J.P. & Geoffroy, L., 2004. Magma flow in the East Greenland dyke swarm inferred from study of anisotropy of magnetic susceptibility: Magmatic growth of volcanic margin, *Geophys. J. Int.*, **159**, 816–830.
- Collier, J.S. *et al.*, 2008. Age of Seychelles–India break-up, *Earth planet. Sci. Lett.*, **272**, 264–277.
- Corfield, R.I. *et al.*, 2010. Variability in the crustal structure of the West Indian Continental Margin in the Northern Arabian Sea, *Petrol. Geosci.*, **16**, 257–265.
- Courtillot, V.E. & Renne, P.R., 2003. On the ages of flood basalt events, *C. R. Geosci.*, **335**, 113–140.
- Daniels, K.A., 2014. Thermal models of dyke intrusion during development of continent–ocean transition, *Earth Plan. Sci. Letters*, **385**, 145–153.
- Eagles, G. & Hoang, H.H., 2014. Cretaceous to present kinematics of the Indian, African and Seychelles plates, *Geophys. J. Int.*, **196**, 1–14.
- Einarsson, P. & Brandsdóttir, B., 1980. Seismological evidence for lateral magma intrusion during the July 1978 deflation of the Krafla volcano in NE-Iceland, *J. Volc. Geotherm. Res.*, **47**, 160–165.
- Foulger, G.R., Gernigon, L. & Geoffroy, L., 2020, submitted. Iceland, in *In the Footsteps of Warren B. Hamilton: New Ideas in Earth Science*, eds Foulger, G.R., Jurdy, D.M., Stein, C.A., Hamilton, L.C., Howard, K., & Stein, S., Geological Society of America.
- Franke, D. *et al.*, 2010. Birth of a volcanic margin off Argentina, South Atlantic, *Geochem. Geophys. Geosyst.*, **11**, Q0AB04.
- Franke, D. *et al.*, 2019. Polyphase magmatism during the formation of the Northern East Greenland Continental Margin, *Tectonics*, **38**(8), 2961–2982.
- Funck, T. *et al.*, 2017. A review of the NE Atlantic conjugate margins based on seismic refraction data, *Geol. Soc. Lond. Spec. Publ.*, **447**, 171–205.
- Gac, S. & Geoffroy, L., 2009. 3D Thermo-mechanical modeling of a stretched continental lithosphere containing localized low-viscosity anomalies (the soft-point theory of plate break-up), *Tectonophysics*, **468**, 158–168.
- Geoffroy, *et al.*, 2001. Southeast Baffin volcanic margin and the North American–Greenland plate separation, *Tectonics*, **20**, 566–584.
- Geoffroy, L., 2005. Volcanic passive margins, *C. R. Geosci.*, **337**, 1395–1408.
- Geoffroy, L., Burov, E.B. & Werner, P., 2015. Volcanic passive margins: another way to break up continents, *Sci. Rep.*, **5**, 14828.
- Geoffroy, L., Gernigon, L. & Foulger, G.R.L., 2020, submitted. Linear magnetic anomalies in oceans: not a proof of oceanic crust, in *In the Footsteps of Warren B. Hamilton: New Ideas in Earth Science*, eds Foulger, G.R., Jurdy, D.M., Stein, C.A., Hamilton, L.C., Howard, K. & Stein, S., Geological Society of America.

- Geoffroy, L., Le Gall, B., Daoud, M.A. & Jalludin, M., 2014. Flip-flop detachment tectonics at nascent passive margin in SE-Afar, *J. Geol. Soc., London*, doi: dx.doi.org/10.1144/jgs2013-135.
- Guan, H., Geoffroy, L. & Werner, P., 2016. Is the Gop-Rift oceanic? A re-evaluation of the Seychelles-India conjugate margin, in *Proceedings of the EGU General Assembly 2016*, 17–22 April 2016 in Vienna, Austria, id. EPSC2016-7643.
- Guan, H.X., Geoffroy, L., Gernigon, L., Chauvet, F., Grigne, C. & Werner, P., 2019. Magmatic ocean-continent transitions, *Mar. Petrol. Geol.*, **104**, 438–450.
- Grandin, R. *et al.*, 2011. Seismicity during lateral dike propagation: insights from new data in the recent Manda Hararo–Dabbahu rifting episode (Afar, Ethiopia), *Geochem. Geophys. Geosyst.*, **12**, Q0AB08, doi:10.1029/2010GC003434.
- Gudmundsson, A., 1983. Form and dimensions of dykes in eastern Iceland, *Tectonophysics*, **95**, 295–307.
- Hammond, J.O.S., *et al.*, 2011. The nature of the crust beneath the Afar triple junction: Evidence from receiver functions, *Geochem., Geophys. Geosyst.*, **12**, doi: 10.1029/2011GC003738.
- Huisman, R. & Beaumont, C., 2011. Depth-dependent extension, two-stage breakup and cratonic underplating at rifted margins, *Nature*, **473**, 74–78.
- Kendall, J.M., Stuart, G.W., Ebinger, C.J., Bastow, I.D. & Keir, D., 2005. Magma-assisted rifting in Ethiopia, *Nature*, **433**(7022), 146–148.
- Klausen, M.B. & Larsen, H.C., 2002. The East Greenland coastal dyke swarm and its role in continental breakup, in *Volcanic Rifted Margins*, Vol. 362, pp. 137–162, eds Menzies M.A., Klemperer S.L., Ebinger C.J., Baker J., Geological Society of America Special Publications.
- König, M. & Jokat, W., 2010. Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potential field data, *Geophys. J. Int.*, **180**, 158–180.
- Krishna, K.S., Gopala Rao, D. & Sar, D., 2006. Nature of the crust in the Laxmi Basin (14°–20° N), western continental margin of India, *Tectonics*, **25**, TC1006.
- Kuszniir, N.J. & Park, R.G., 1987. The extensional strength of the continental lithosphere: its dependence on geothermal gradient, and crustal composition and thickness, *Geol. Soc., Lond., Spec. Publ.*, **28**, 35–52.
- Larsen, H.C. & Jakobsdóttir, S., 1988. Distribution, crustal properties and significance of seawards-dipping sub-basement reflectors off E Greenland, *Geol. Soc. Lond., Spec. Publ.*, **39**, 95–114.
- Lenoir, X., Féraud, G. & Geoffroy, L., 2003. High-rate flexure of the East Greenland volcanic margin: constraints from $^{40}\text{Ar}/^{39}\text{Ar}$ dating of basaltic dykes, *Earth planet. Sci. Lett.*, **214**, 515–528.
- Manighetti, I., *et al.*, 2001. Strain transfer between disconnected propagating rifts in Afar, *J. of Geophys. Res.*, **106**:13613–13665.
- McDermott, C., Lonergan, L., Collier, J.S., Kenneth, G., McDermott, K.G. & Bellingham, P., 2018. Characterization of seaward-dipping reflectors along the South American Atlantic margin and implications for continental breakup, *Tectonics*, **37**, 3303–3327.
- Minshull, T.A., Lane, C.I., Collier, J.S. & Whitmarsh, R.B., 2008. The relationship between rifting and magmatism in the northeastern Arabian Sea, *Nat. Geosci.*, **1**, 463.
- Misra, A.A., Sinha, N. & Mukherjee, S., 2015. Repeat ridge jumps and microcontinent separation: insights from NE Arabian Sea, *Mar. Petrol. Geol.*, **59**, 406–428.
- Misra, A.A., Banerjee, S., Kundu, N. & Mukherjee, B., 2017. Subsidence around oceanic ridges along passive margins: NE Arabian Sea, *Geol. Soc., Lond., Spec. Publ.*, **445**, 119–149.
- Mutter, J.C., Talwani, M. & Stoffa, P.L., 1982. Origin of seaward-dipping reflectors in oceanic crust off the Norwegian margin by ‘subaerial seafloor spreading’, *Geology*, **10**, 353–357.
- Nemčok, M. & Rybár, S., 2016. Rift-drift transition in a magma-rich system: the Gop Rift–Laxmi basin case study, West India, *Geol. Soc. Spec. Publ.*, **445**, 95–117.
- Naini, B.R. & Talwani, M., 1982. Structural Framework and the evolutionary history of the continental margin of western India, *AAPG Mem.*, **34**, 167–191.
- Pagli, C., Wright, T., Ebinger, C., Yun, S.-H., Cann, J.R., Barnie, T. & Ayele, A., 2012. Shallow axial magma chamber at the slow-spreading Erta Ale Ridge, *Nat. Geosci.*, **5**, 284–288.
- Palmason, G., 1981. Crustal rifting, and related thermo-mechanical processes in the lithosphere beneath Iceland, *Geol. Rundsch.*, **70**, 244–260.
- Paton, D.A., Pindell, J., McDermott, K., Bellingham, P. & Horn, B., 2017. Evolution of seaward-dipping reflectors at the onset of oceanic crust formation at volcanic passive margins: insights from the South Atlantic, *Geology*, **45**, 439–442.
- Pérez-Gussinyé, M., Metois, M., Fernández, M., Vergés, J., Fulla, J. & Lowry, A.R. 2009. Effective elastic thickness of Africa and its relationship to other proxies for lithospheric structure and surface tectonics, *Earth planet. Sci. Lett.*, **287**, 152–167.
- Pindell, J., Graham, R. & Horn, B., 2014. Rapid outer marginal collapse at the rift to drift transition of passive margin evolution, with a Gulf of Mexico case study, *Basin. Res.*, **26**, 701–725.
- Planke, S., Symonds, P.A., Alvestad, E. & Skogseid, J., 2000. Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins, *J. geophys. Res.*, **105**, 19 335–19 351.
- Quirk, D.G., Shakerley, A. & Howe, M.J.A., 2014. Mechanism for construction of volcanic rifted margins during continental breakup, *Geology*, **42**, 1079–1082.
- Rey, S.S., Planke, S., Symonds, P.A. & Faleide, J.I., 2008. Seismic volcanostratigraphy of the Gascoyne margin, Western Australia, *J. Volc. Geotherm. Res.*, **172**(1–2), 112–131.
- Stab, M., Bellahsen, N., Pik, R., Quidelleur, X., Ayalew, D. & Leroy, S., 2016. Modes of rifting in magma-rich settings: tectono-magmatic evolution of Central Afar, *Tectonics*, **35**, 2–38.
- Sager, W.W., 2014. Scientific Drilling in the South Atlantic: Rio Grande Rise, Walvis Ridge and surrounding areas, US Science Support Program.
- Schnabel, M. *et al.*, 2008. The structure of the lower crust at the Argentine continental margin, South Atlantic at 44 degrees S, *Tectonophysics*, **454**, 14–22.
- Skogseid, J., 2001. Volcanic margins: geodynamic and exploration aspects, *Mar. Petrol. Geol.*, **18**, 457–461.
- Sigmundsson, F. *et al.*, 2014. Segmented lateral dyke growth in a rifting event at Bárðunga volcanic system, Iceland, *Nature*, **517**(7533), 191–195.
- Stica, J.M., Zalán, P.V. & Ferrari, A.L., 2014. The evolution of rifting on the volcanic margin of the Pelotas Basin and the contextualization of the Paraná–Etendeka LIP in the separation of Gondwana in the South Atlantic, *Mar. Petrol. Geol.*, **50**, 1–21.
- Soto, M., Morales, E., Veroslavsky, G., de Santa Ana, H., Ucha, N. & Rodríguez, P., 2011. The continental margin of Uruguay: crustal architecture and segmentation, *Mar. Petrol. Geol.*, **28**(9), 1676–1689.
- Talwani, M. & Reif, C., 1998. Laxmi ridge – a continental sliver in the Arabian Sea, *Mar. Geophys. Res.*, **20**, 259–271.
- White, R. *et al.*, 2008. Lower-crustal intrusion on the North Atlantic continental margin, *Nature*, **452**, 460–464.
- Wolfenden, E., Ebinger, C., Yirgu, G., Renne, P.R. & Kelley, S.P., 2005. Evolution of a volcanic rifted margin: southern Red Sea, Ethiopia, *Bull. geol. Soc. Am.*, **117**, 846–864.
- Wright, T., Ebinger, C., Biggs, J., Ayele, A., Yirgu, G., Keir, D. & Stork, A., 2006. Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode, *Nature*, **442**, 291–294.
- Wrona, T. *et al.*, 2019. 3-D seismic images of an extensive igneous sill in the lower crust, *Geology*, **47**, 729–733.